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Volume 1 Executive Summary

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16. Abstract

This paper presents an insight into auxiliary propulsion systems (APS) requirements for large space systems (LSS) launchable by a single shuttle. In an effort to scope the APS requirements for LSS, a set of generic LSSs were defined. For each generic LSS class a specific structural configuration, representative of that most likely to serve the needs of the 1980's and 1990's was defined. The environmental disturbance forces and torques which would be acting on each specific structural configuration in LEO and GEO orbits were then determined. Auxiliary propulsion requirements were determined as a function of: generic class specific configuration, size and openness of structure, orbit, angle of orientation, correction frequency, duty cycle, number and location of thrusters and direction of thrusters and APS/LSS interactions. The results of this analysis were used to define the APS characteristics of: (1) number and distribution of thrusters, (2) thruster modulation, (3) thrust level, (4) mission energy requirements, (5) total APS mass component breakdown, and (6) state-of-the-art adequacy/deficiency.

17. Key Words (Suggested by Author(s))

Attitude Control, Auxiliary Propulsion, Large Space Structures, Shape Control, Stationkeeping

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FOREWORD

This Executive Summary was prepared by the Boeing Aerospace Company, meeting the requirements of Contract NAS3-23248. The contract is administered by the Lewis Research Center of the National Aeronautics and Space Administration, Cleveland, Ohio. Mr. J. E. Maloy was the NASA Project Manager.

The Boeing Aerospace Program Manager, W. W. Smith, wishes to acknowledge contributions by the following individuals to this program: G. W. Machles for his dedication to the program as the principal investigator, Lisa DeBra for her structural analysis and interactions contribution, and David Zabloudil for his dynamics and environmental torque analysis.

BACKGROUND

With increasing fervor, plans to utilize the resources of space are being made within NASA, DOD and private industry. Many of these plans call for the use of Large Space Systems (LSS) to accomplish a wide variety of goals. These LSS will require new technology in hardware and analysis techniques to be enabled and utilized in the most cost effective fashion. To assess the propulsion technology requirements and recommend high leverage advances in propulsion, a study was performed examining auxiliary propulsion requirements for a range of single shuttle launched LSS.

OBJECTIVE

The primary objective of the study is to determine the auxiliary propulsion requirements of deployable LSS with missions in the 1990-2010 time frame. The main emphasis will be on LSS which can be launched with a single shuttle flight. By establishing the auxiliary propulsion requirements for a range of LSS missions, the study can serve as a useful guideline for the initiation of future technology development programs. The study will ensure that state-of-the-art space propulsion capability keeps pace with the needs of various STS user communities.

KEY ISSUES

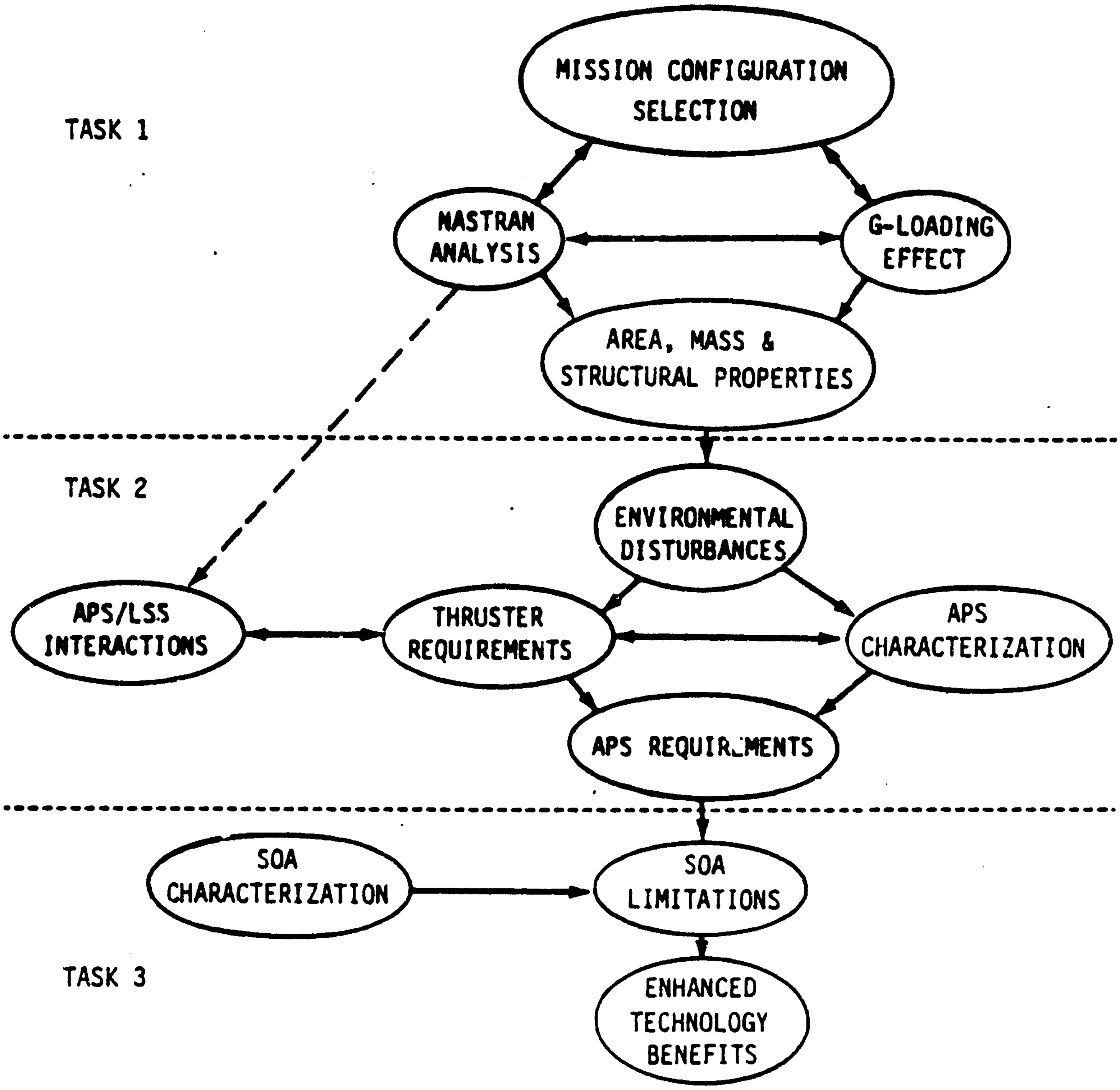
- Structural modeling
- LEO deployment and operation
- GEO operation
- APS system mass impacts
- Technology areas to improve

KEY ASSUMPTIONS

- Single shuttle launched (exception SOC, SASP)
- Advanced preliminary design deployable LSS
- LEO (300-500 km) and GEO operatoin
- NASA neutral atmospheric model assumed
- Only well established propulsion options examined (monopropellant, bipropellant, ion)
- No factors of conservatism were employed

The key issues listed point out the importance of structural modeling and operational concerns on propulsion requirements. Large space systems have more challenging performance requirements and more flexibility than most smaller spacecraft. No contingencies were used to determine propellant loads or thrust requirements because the assignment of such factors would be arbitrary and trends indicated from these results would not be affected for small contingency assignments.

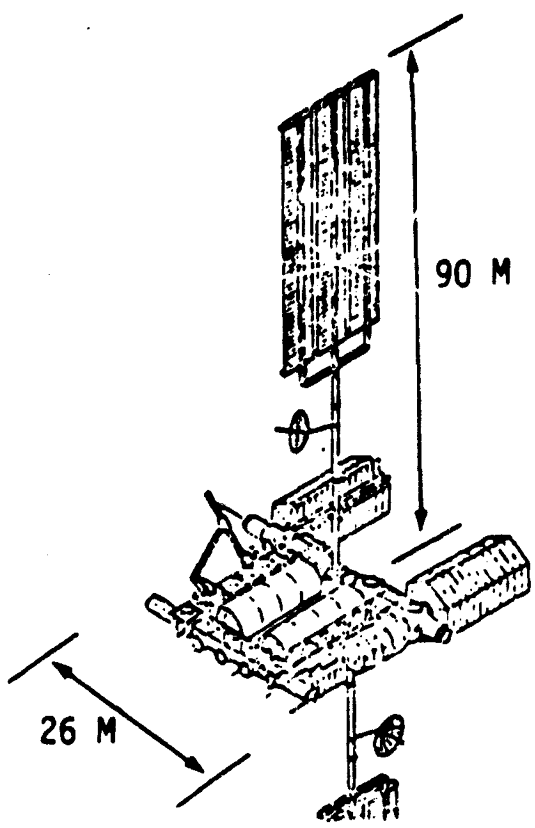
PROGRAM TASK FLOW



Task 1 determined the relevant missions and spacecraft properties which would be used to define propulsion requirements. The NASTRAN models and associated loads analysis gave us an insight into the variation of mass with primary thrust g-loading and were also used to determine the APS/LSS interactions in Task 2. Thrust requirements, impulse bit requirements, I_{sp} effects and hardware masses were determined in Task 2. These requirements were compared with current capabilities and a set of limitations found in Task 3. The benefits in terms of enhanced mission capture and reduced APS mass were assessed in the final analysis of Task 3.

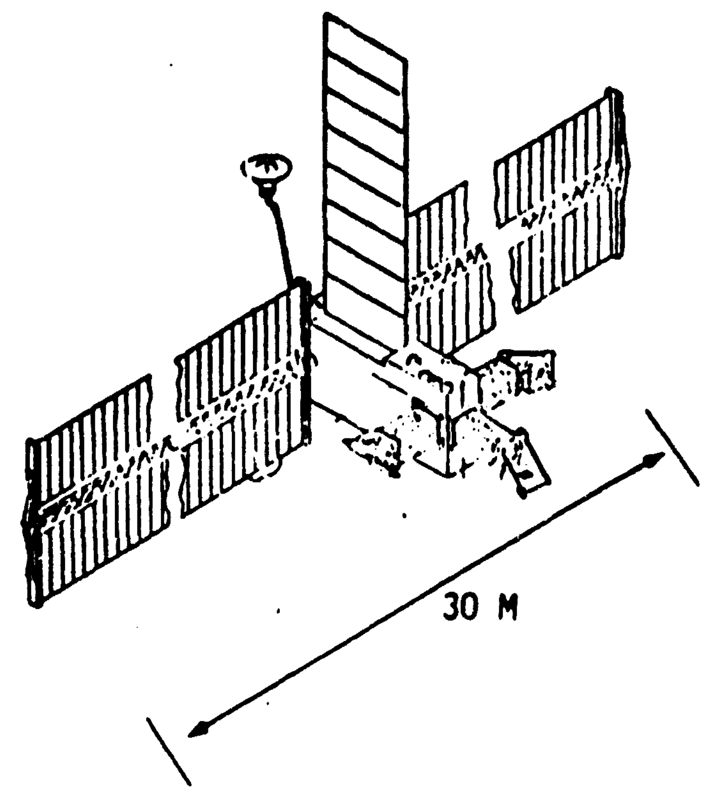
SPACE PLATFORM CLASSES

SOC - Operational



- REPRESENTATIVE SPACE STATION DESIGN
- VERY LARGE MASS, INERTIAS
- LOW A/M

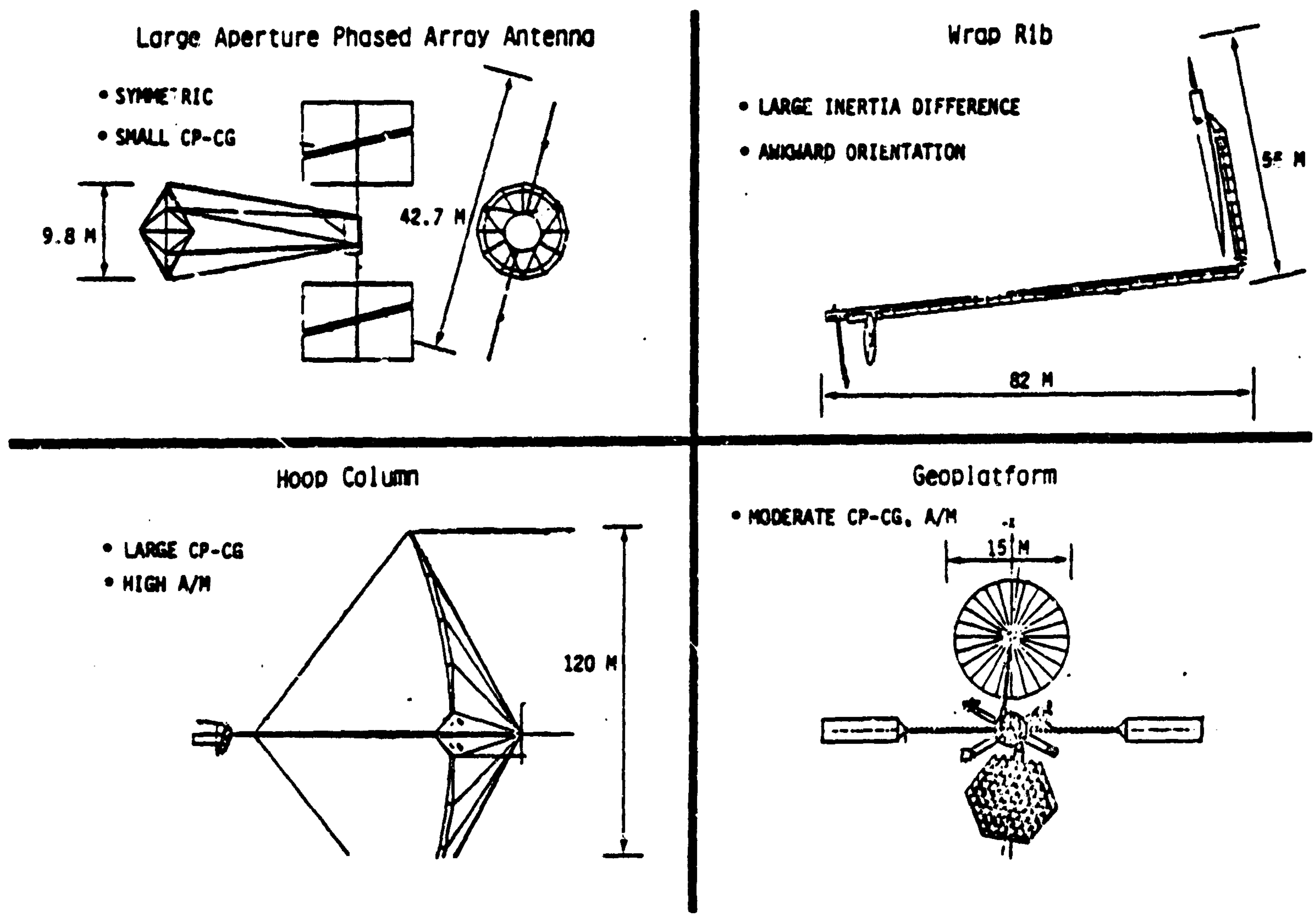
SASP



- REPRESENTATIVE SPACE PLATFORM DESIGN
- LARGE MASS, MODERATE INERTIAS
- MODERATE A/M

Two space platform classes were examined which violated the single shuttle launch criteria. This was done to understand the LEO requirements of this broad class of platforms. Two sizes of each platform were examined - initial and operational SOC designs and a 12.5 kw and 25 kw SASP design.

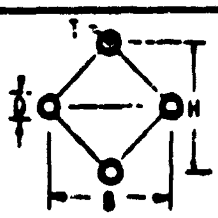
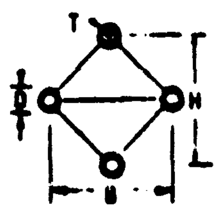
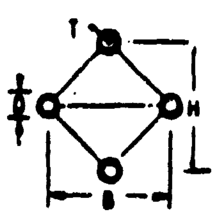
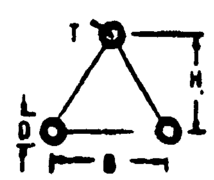
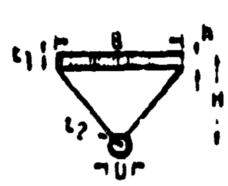
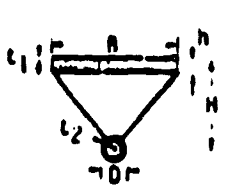
ANTENNA SYSTEMS SELECTION



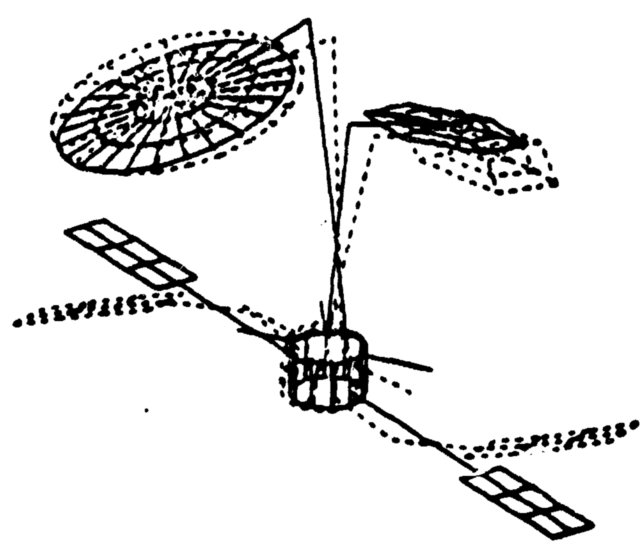
The above structures represent such widely varying missions as Space Based Radar, Educational TV, and Land Mobile Satellite Services. Individual structures such as the offset feed Wrap Rib design may perform more than one mission; however, many propulsion requirements and interactions problems will be similar. All structures chosen were of sufficient level of detail to allow NASTRAN modeling.

NASTRAN MODELING

EXAMPLE SECTION PROPERTIES - GEOPLATFORM

MEMBER	VIEW OF X-SECTION	NASTRAN ELEMENT	DESCRIPTION	MATERIAL*
WRAP RIB & PETA VERTICAL TRUSSES		BAR	CONVAIR DEPLOYABLE TRUSS H = 1.25 m B = 0.89 m D = 0.019 m T = 0.0015 m	GR/EP
WRAP RIB HORIZONTAL TRUSS		BAR	CONVAIR DEPLOYABLE TRUSS H = 0.94 m B = 0.67 m D = 0.016 m T = 0.00081 m	GR/EP
SOLAR ARRAY ASTROMASTS		BAR	CONVAIR DEPLOYABLE TRUSS H = 0.25 m B = 0.35 m D = 0.006 m T = 0.0015 m	GR/EP
SOLAR ARRAY SUPPORT BOOMS		BAR	½ GD TRUSS H = 0.47 m B = 0.67 m D = 0.019 m T = 0.0015 m	GR/EP
SPACE RAILS FOR RADIATOR & P/L 301		BAR	CONVAIR SPACE RAIL h = 0.08 m H = 0.4 m B = 0.8 m t_1 = .0005 m D = .010 m t_2 = .0008 m	GR/EP
SPACE RAILS FOR P/L 501, P/L 502 & P/L 604		BAR	CONVAIR SPACE RAIL h = .06 m H = .3 m B = .6 m t_1 = .0005 m D = .010 m t_2 = .0008 m	GR/EP

Sample NASTRAN Output - Geoplatform



EXPERIMENTAL GEOSTATIONARY PLATFORM
3RD MODE - 0.145 HZ

NASTRAN modeling was based on the assumption that the lowest structural mode would be .1 Hz or greater and that structural elements would be sized for .15 g's (primary thrust). These values were consistent with the masses and structural frequencies found in the literature for each structural element.

ENVIRONMENTAL DISTURBANCE TORQUES

• TORQUES (N-M)

	LEO (400 KM)		LEO (500 KM)		GEO	
	NOMINAL	WORST CASE	NOMINAL	WORST CASE	NOMINAL	WORST CASE
LAPAA 13 KM	.5	.8	.2	.4	.004	.044
LAPAA 65 KM	3	4	.9	1	.009	.009
WRAP RIB 55M	10	20	6	9	.06	.06
HOOP/COLUMN 120 M	20	30	6	10	.04	.05
GEOSTATIONARY PLT.	1	2	.3	.8	.003	.007
SASP 12.5 KW	1	4	.4	1	N/A	N/A
SASP 25 KW	2	7	.7	2	N/A	N/A
SOC INITIAL	40	40	10	10	N/A	N/A
SOC OPERATIONAL	10	20	4	10	N/A	N/A

Environmental disturbance torques were dominated by aerodynamics at 400 km altitude and to a lesser degree at 500 km. Gravity gradient torque was the primary source at GEO. Two orientations are shown, a nominal or operational attitude, and a worst case attitude which yields the highest RSS torque from all contributions. For some spacecraft the nominal and worst case torques are not widely separated. This indicates some reconfiguration to allow more inertial symmetry or smaller effective CP-CG moments would yield smaller momentum management and propellant requirements for 3-axis control.

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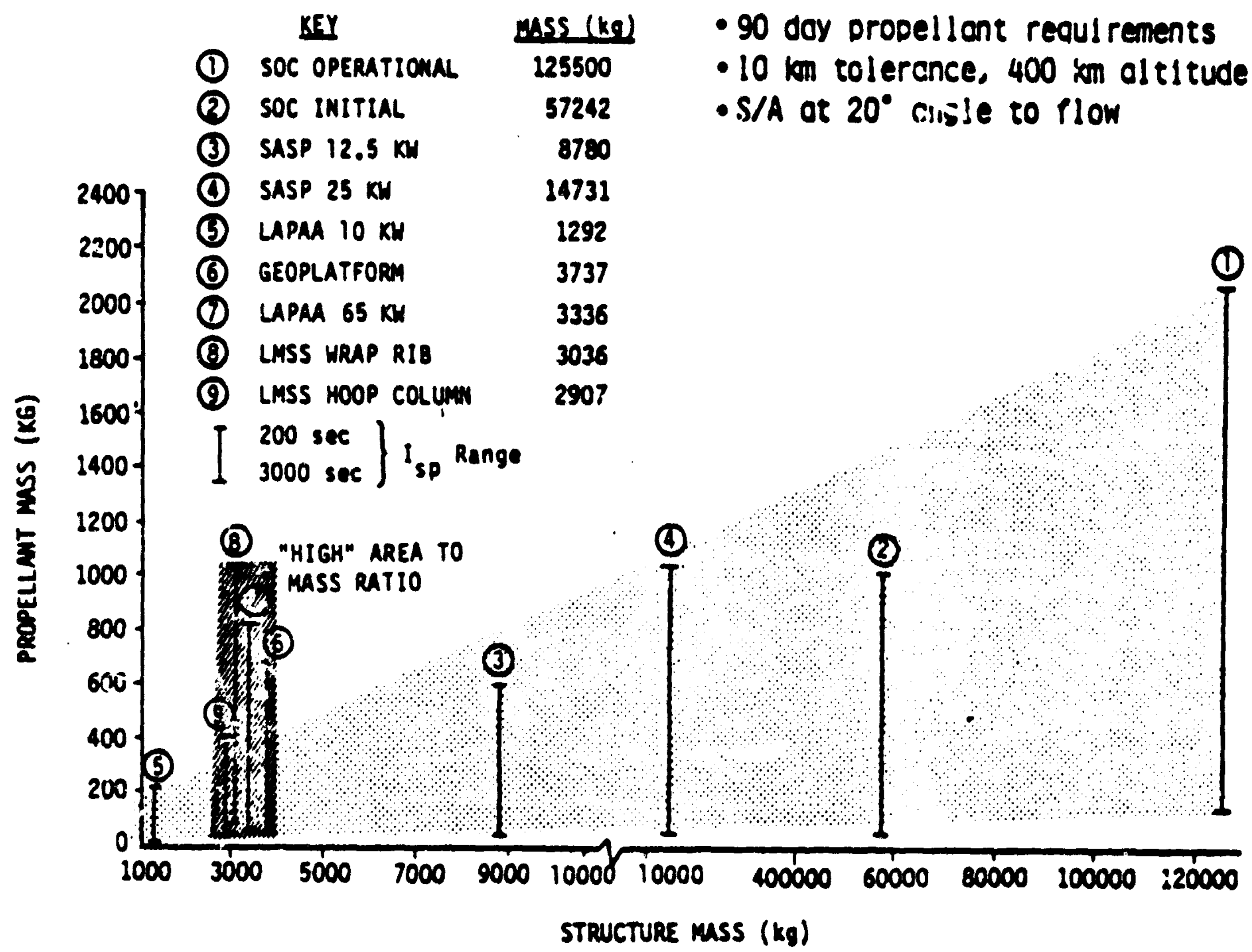
LEO STATIONKEEPING PROPELLANT REQUIREMENTS



Propellant requirements for LEO checkout or operation can be very significant. The tolerance on the altitude used above allowed the spacecraft to drop 10 km in orbit altitude before impulsive reboost. All solar arrays were held at a 20 degree angle of attack corresponding to a reduced frontal area due to sun tracking and feathering on the dark side. The high area to mass configuration required 15 to 35% of the structure mass for N_2H_4 stationkeeping propellant for short stays in LEO. This mass coupled with the radically different LEO and GEO thrust levels makes full LEO deployment and checkout have large impact on propulsion system design cost.

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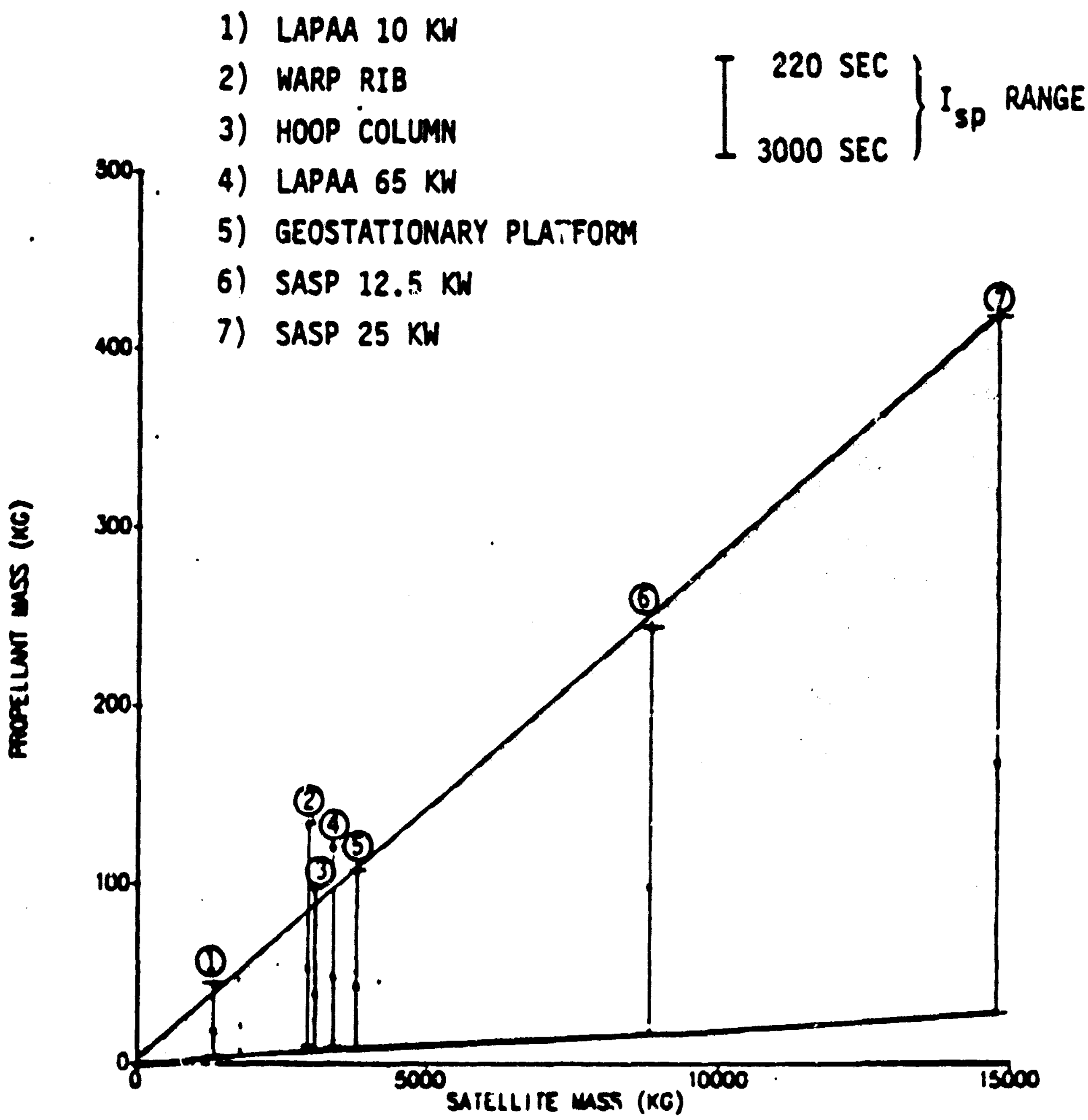
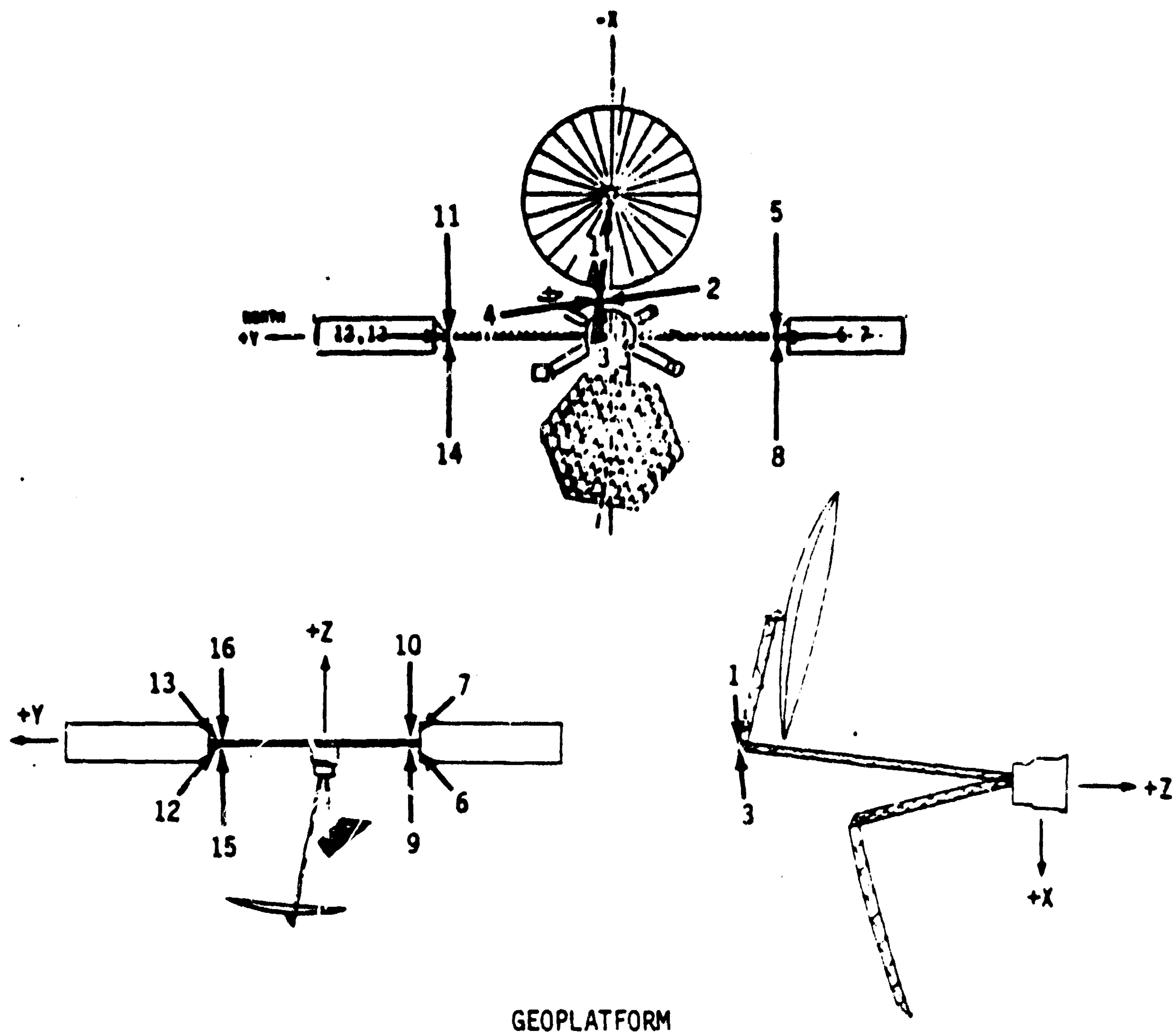
GEO STATIONKEEPING PROPELLANT REQUIREMENTS

- PROPELLANT FOR 1 YEAR
- DUTY CYCLE = 1%
- .1 DEG LAT, LONG EXCURSION



GEO propellant requirements are roughly proportional to satellite mass. The numbers show that for a 10 year mission, propellant mass ranges from 13 to 35% of total system mass using N_2H_4. This percentage indicates that large savings can be realized by going to higher I_{sp}'s as long as powe ror propellant storage mass remains low. Solar contributions to E/W stationkeeping are significant for area/mass ratios of .1 or greater and are seen in spacecraft 2, 3, and 4. The duty cycle used is very short (15 minutes/orbit); however, much longer duty cycles can be used before cosine losses become significant.

THRUSTER LOCATIONS



GEOPLATFORM

The representative thrust locations shown above result from the application of seven location criteria. These criteria can be summarized by three statements; maximum moment arms employed without S/A mounting, 3-axis control and N/S-E/W delta-V required, and independent torque and delta-V in all axis required. In retrospect it was found that the criteria of using maximum moment arms was not required because the disturbance levels did not grow as fast as the moment arms for LSS. This in fact drove minimum impulse bit requirements below the state-of-the-art.

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THRUST/THRUSTER RANGE FOR STATIONKEEPING

- THRUST/THRUSTER IN NEWTONS
- DATA FOR .15 g STRUCTURE

	LEO (400 km) Thrust Time = ½ Hour	GEO Correction Frequency = Once/Week			
		Duty Cycle = .01		Duty Cycle = .4	
		N/S	E/W	N/S	E/W
ELECTRONIC MAIL	.8 - 3	.4 - .5	.005 - .02	.01	.0001 - .0005
EDUCATIONAL TV	.7 - 7	.4 - 2	.006 - .06	.01 - .04	.0002 - .002
WRAP RIB	1 - 8	.4 - 2	.008 - .02	.01 - .06	.0002 - .001
HOOP COLUMN	2 - 6	.7 - 2	.02 - .04	.02 - .04	.0005 - .001
GEOSTATIONARY PLT.	3 - 7	.9 - 2	.02 - .04	.02 - .06	.0005 - .001
SOC INITIAL	4 - 60	10 - 30	N/A	N/A	N/A
SOC OPERATIONAL	3 - 100	20 - 40	N/A	N/A	N/A

LEO thrust/thruster requirements were significantly higher than even GEO requirements using very short (15 minute) duty cycles. When compared to the E/W and longer duty cycle N/S requirements, LEO propulsion requirements were orders of magnitude larger than GEO requirements. It is also seen that a range of thrust levels was required to meet stationkeeping delta-V with 0 torque. This is due to the lack of symmetry of most designs and consequent unequal thruster moment arms. A throttling range was therefore identified for each LSS class which ranged up to 6:1. This table shows that high thrust (> 2N/thruster) is not required for most LSS for GEO operation only.

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APS MASS REQUIREMENTS FOR GEO STATIONKEEPING

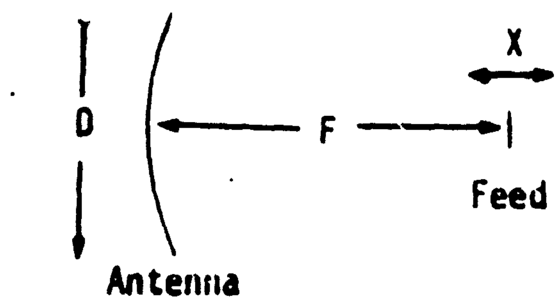
• 10 YEAR OPERATION

	Mass of Satellite	1% Duty Cycle APS Mass (kg)	1% Duty Cycle Total Mass (kg)	1% Duty Cycle % APS	40% Duty Cycle APS Mass (kg)	40% Duty Cycle Total Mass (kg)	40% Duty Cycle % APS
LAPAA 10 KW	1292						
monopropellant		506	1798	28.1	546	1838	29.7
bipropellant		356	1648	21.6	383	1675	22.9
electrical propulsion		14858	16150	92	59.5	1351.5	4.4
LAPAA 65 KW	3336						
monpropellant		1385	4721	29.3	1495	4831	30.9
bipropellant		972	4308	22.6	1045	4381	23.9
electrical propulsion		No Convergence			197.9	3533.9	5.6
LMSS Wrap Rib	3036						
monopropellant		1073	4109	26.1	1156	4192	27.6
bipropellant		758	3794	20.0	814	3850	21.1
electrical propulsion		No Convergence			214.5	3250.5	6.6
LMSS Hoop Column	2907						
monopropellant		1641	4548	36.1	1779	4686	38.0
bipropellant		1134	4041	28.1	1224	4131	29.6
electrical propulsion		No Convergence			212.1	3119.1	6.8
Geostationary Platform	3737						
monopropellant		1164	4901	23.8	1253	4990	25.1
bipropellant		826	4563	18.1	886	4623	19.2
electrical propulsion		No Convergence			234.3	3971.3	5.9
SOC Initial	57242						
monopropellant		14890	72132	20.6	16000	73242	21.9
bipropellant		10590	67832	15.6	11360	68602	16.6
electrical propulsion		No Convergence			2823.1	60065.1	4.7
SOC Operational	125500						
monopropellant		32490	157990	20.6	34910	160410	21.8
bipropellant		23110	148610	15.6	24780	150280	16.5
electrical propulsion		376500	502000	75	4821.9	130321.9	3.7

APS mass for monopropellant (I_{sp} = 220 sec), bipropellant (I_{sp} = 300 sec), and ion systems (I_{sp} = 3000 sec) for a 10 year GEO mission is shown. Two duty cycles which correspond to two different thrust/thruster levels and slightly different delta-V requirements are included. Chemical systems are between 20-40% of total system mass for both duty cycles. Ion systems show a strong dependence on duty cycle because of the dominance of power system mass at short duty cycles (hence high thrust). For the 1% duty cycle, meaning 15 minutes/orbit, power system mass was rising to unrealistic levels and the algorithm used to calculated APS mass did not converge. If electric systems are to yield significant mass advantages, long duty cycles with autonomous operation is required.

ANTENNA DEFOCUSING DEFINITIONS

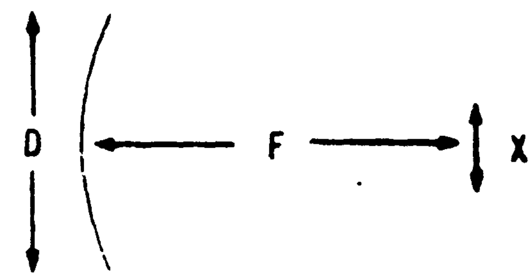
DESPACING



Definition: ΔLongitudinal distance between feed & antenna.

Impact: Phase error and gain loss & broadening of beam.

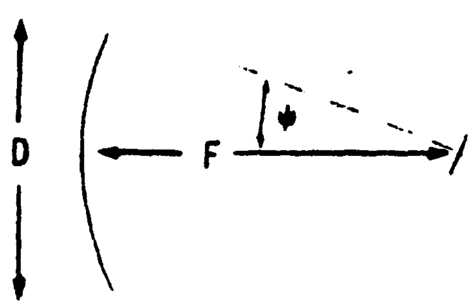
DECENTER



Definition: ΔLattitudinal distance feed/antenna.

Impact: Pointing loss; no gain loss unless ΔX gets larger than the beamwidth.

TILT



Definition: ΔAngle between focal line of feed and focal line of antenna.

Impact: Changes energy distribution across reflector - generally will even out.

After the thrust/thruster requirements were established, the interactions between the structure and the thrusters were analyzed in terms of antenna defocusing. Defocusing was broken into three separate calculable deformations. A fourth source of defocusing was surface deformation of the antenna mesh. This source was not analyzed due to time and funding limitations. Defocusing sensitivities were generated as a function of broadcast wavelength and focal length/diameter ratio. These sensitivities were used to calculate power loss in the beam for each large antenna system.

APS/LSS INTERACTIONS RESULTS

LARGE APERTURE PHASED ARRAY

Conditions	Decenter (meters)	Despace (meters)	Tilt (radians)
6.96 N/Thruster	.0612	.0001	.0069
2.0 N/Thruster	.0183	.0000	.0022

HOOP COLUMN LMSS

Conditions	Decenter (meters)	Despace (meters)	Tilt (radians)
30.0 N/Thruster	.5361	.0025	.0069
2.0 N/Thruster	.0357	.0001	.0005

WRAP RIB LMSS

Conditions	Decenter (meters)	Despace (meters)	Tilt (radians)
8.12 N/Thruster	.113	.0018	.1939
2.0 N/Thruster	.0286	.0008	.0633

GEOSTATIONARY PLATFORM

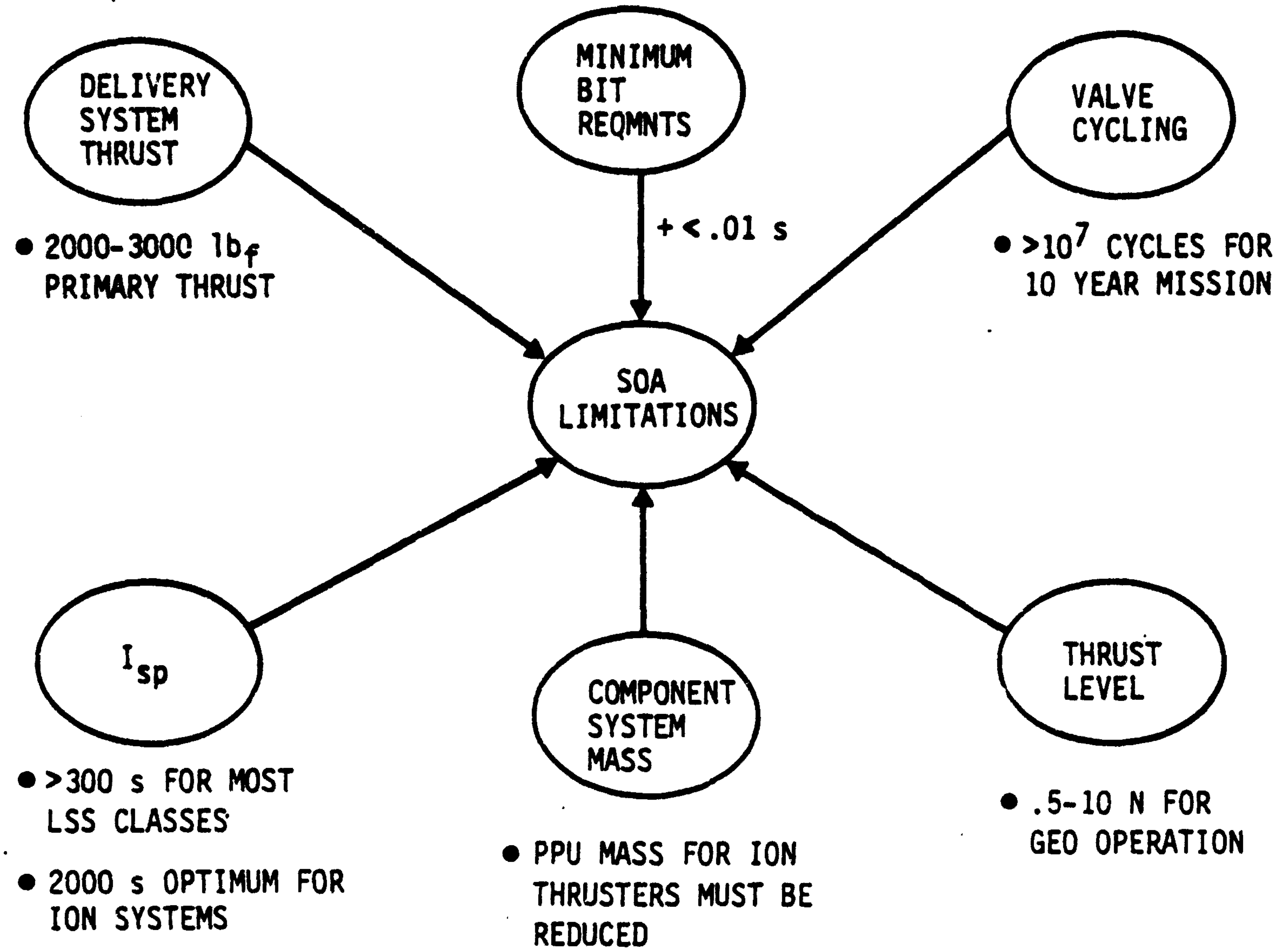
Conditions	Decenter (meters)	Despace (meters)	Tilt (radians)
7.2 N/Thruster	.0043	.0024	.0541
2.0 N/Thruster	.0012	.0006	.0001

5% POWER LOSS

≥ 10% POWER LOSS

For each antenna system the NASTRAN models and thruster locations were coupled to perform a dynamic simulation. Thrust levels for the stationkeeping thrusters (4 used) were set at two levels corresponding to a LEO thrust level with .5 hour duty cycle/orbit and a GEO thrust level with a 1% or 15 minute duty cycle/orbit. Significant interaction was found for the wrap rib and hoop column designs. These interactions preclude the use of stationkeeping thrusters of these magnitudes while operating the antenna.

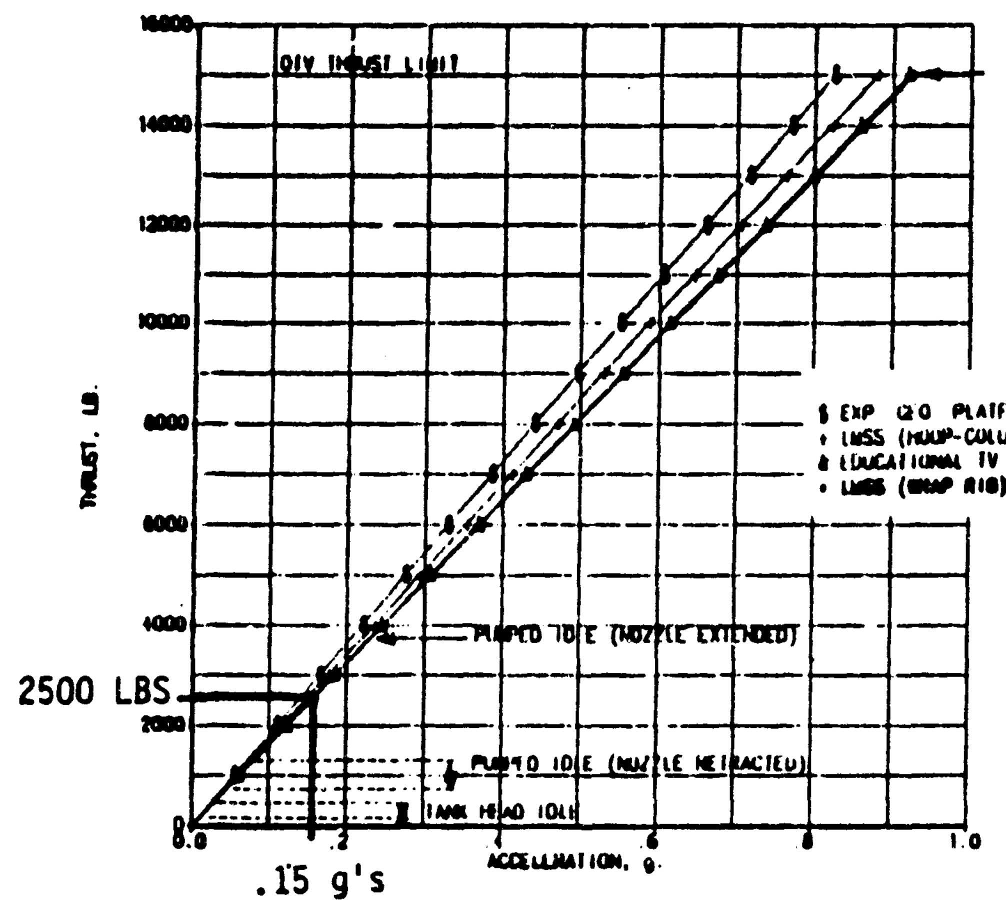
STATE-OF-THE-ART LIMITATIONS



The limitations identified in this study fall into these six categories. Other areas of conern were implicated such as long duty cycle, autonomous operation, and active control of structural interactions.

TRANSFER VEHICLE THRUST REQUIREMENT

- Deployed LSS require low thrust
- 2500 lb thrust maximum for .15 g's



The preliminary designs identified in this study had fully deployed loading capabilities of between .1 and .2 g's (steady state). These numbers were derived from NASTRAN analysis. The limiting elements on these systems were primarily antenna support booms. By not fully deploying the antenna, or in some cases solar arrays, this 'g' load limitation could be raised. For fully deployed LSS, however, 2500 lbs thrust was the maximum allowed. This indicates the need for a 2000-3000 lb_f engine.

VALVE CYCLING/MINIMUM FIRING TIME LIMITATIONS

Class	VALVE CYCLES Firing Time (s) .006	.01	.04	FIRING TIME APS=MMD (I_{sp}=220)	Time Req'd (s) Single Pulse (GEO 1% DC)
Electronic Mail	3.1 E+6	5.2E+6	2.06E+7	.018	1.3 E-5
Educational TV	1.4 E+6	2.3E+6	4.7 E+6	.012	4.2 E-5
LMSS Wrap Rib	3.1 E+6	5.2E+6	1.0 E+7	.023	2.6 E-3
LMSS Hoop Column	3.8 E+5	6.3E+5	2.5 E+6	.022	6.1 E-6
Geoplatform	1.10E+6	8.4E+5	3.4 E+6	.009	2.9 E-4

Indicates SOA Deficiency

Using a standard of 1 x 10^6 cycles lifetime and .01 seconds minimum firing time, state-of-the-art deficiencies were identified in lifetime and minimum bit. The valve cycle requirements shown in the first section of the above table were calculated for a range of firing times given a 10 year mission using 3-axis jet control and GEO 1% duty cycle thrust levels. The firing times required, shown in the second section of the table, fall into two categories. The first column shows the firing time required for the propellant mass to equal a momentum system (reaction wheels) mass. The minimum propellant system mass requires an even shorter thrust pulse as shown in the last column. This minimum mass was a factor of 4 to 10 lower than the momentum system mass. From this table it can be seen that valve cycling capabilities of 2 x 10^7 cycles and firing times of .009 or less would make APS competitive to MMD's.

The following figure shows the approximate regions of the state-of-the-art capability in chemical and electric systems. The systems in development, resistojets and stored inert gasses were not considered in the APS scaling exercise. Overlaid on the capabilities map is the recommended thrust and I_{sp} regime for the classes studied. Due to the uncertainties inherent in the forecasts based on preliminary design, a large region of crosshatching extends the recommended region. A fundamental lower limit in I_{sp} for a 10 year mission results from STS-Centaur G' mass delivery limitations for most of the classes analyzed. An upper limit in I_{sp} is shown which indicates power system mass (including the power source and processing hardware) becomes dominant over propellant mass for ion systems. This limit varies with thrust level requirements and longer duty cycles of 2-5 hours/orbit would raise this limit. In addition, lower PPU specific mass would increase the I_{sp} limit to include existing ion thrusters.

Thrust level limitations vary greatly with LSS class and duty cycle. The lower limit range shown is for N/S stationkeeping with a long 9 hour/orbit duty cycle. Only the pulsed plasma class violates this range of limitations. Thruster lifetime limits for ion thrusters are also violated at these long duty cyles. For ion thrusters this limit is reached for a 10 year mission at duty cycles of only 5 hours/orbit. The region of structural interactions limits thrust/thruster to less than 10 N. This limit only applies to the large flexible antennas which must operate during a stationkeeping maneuver.

In conclusion, this chart shows that propulsion systems such as augmented N_2H_4 and other forms of resistojets, low thrust bipropellants, and possibly low I_{sp} ion systems are in line with LSS requirements.

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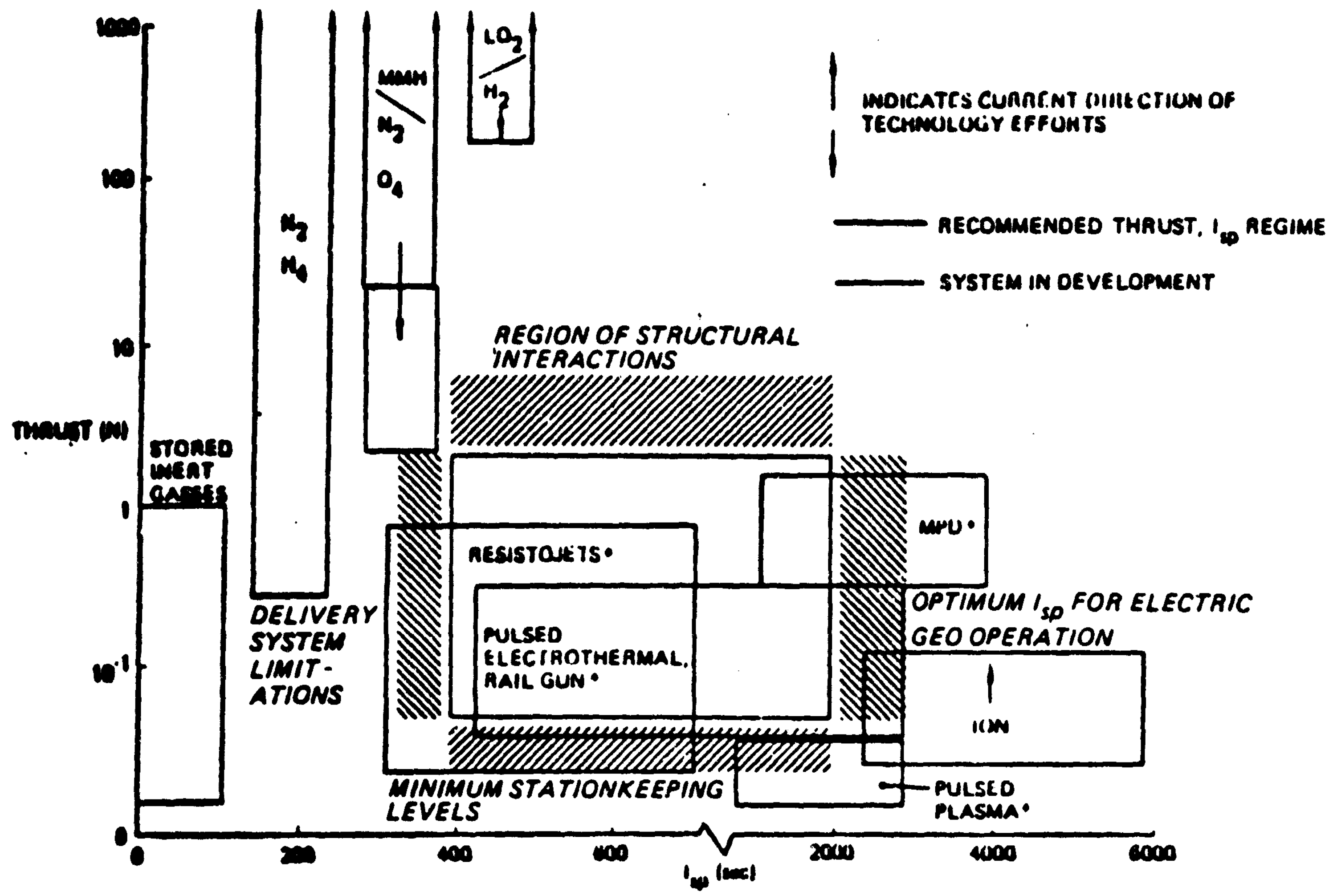
SOA Capability/Requirements Map



• NOT TREATED IN THIS STUDY